EUROASIA JOURNAL OF SOCIAL SCIENCES & HUMANITIES | ISSN: 2651-5261
Arrival Date: 28.01.2025 | Published Date: 24.02.2025 | Vol: 12, Issue: 1 | pp: 51-64
Doi Number: http://doi.org/10.5281/zenodo.14926405

Enerji Verimliliği, Yenilenebilir Enerji ve Çevresel Sürdürülebilirlik: Türkiye Üzerine Bir Analiz

Energy Efficiency, Renewable Energy and Environmental Sustainability: An Analysis on Türkiye

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Özet

Bu çalışma, Türkiye'nin enerji sektöründe enerji verimliliği, yenilenebilir enerji tüketimi ve karbon emisyonları arasındaki ilişkileri inceleyerek çevresel sürdürülebilirlik açısından politika önerileri geliştirmeyi amaçlamaktadır. Çalışmada, 2000-2022 yıllarına ait veriler kullanılmış ve Dickey-Fuller Generalized Least Squares (DF-GLS) birim kök testi ile Toda-Yamamoto nedensellik testi gibi ekonometrik yöntemler uygulanmıştır. Analiz sonuçlarına göre, enerji verimliliği ile karbon emisyonları arasında %5 anlamlılık düzeyinde tek yönlü bir nedensellik ilişkisi tespit edilmiştir. Bu sonuç, enerji verimliliğinin karbon emisyonlarını azaltmada etkili bir araç olduğunu ortaya koymuştur. Öte yandan, yenilenebilir enerji tüketimi ile karbon emisyonları arasında anlamlı bir nedensellik ilişkisi bulunmamıştır. Bu durum, yenilenebilir enerji altyapısının geliştirilmesi ve bu alandaki politikaların güçlendirilmesi gerektiğini işaret etmektedir. Çalışma, enerji verimliliği ve yenilenebilir enerji politikalarının etkilerinin ülkeye özgü koşullardan etkilendiğini vurgulamaktadır. Türkiye'nin enerji sektörü bağlamında, enerji tasarrufu sağlayan teknolojilerin teşvik edilmesi, yenilenebilir enerji yatırımlarının artırılması ve karbon vergisi gibi çevresel politikaların uygulanması önerilmektedir. Ayrıca, uluslararası işbirliklerinin artırılması ve bölgesel düzeyde yenilenebilir enerji projelerinin geliştirilmesi gerektiği belirtilmiştir. Bu öneriler, Türkiye'nin sürdürülebilir kalkınma hedeflerine ulaşmasına katkı sağlayabilir. Çalışma, literatüre enerji verimliliğinin karbon emisyonları üzerindeki etkisi ve yenilenebilir enerji politikalarının etkinliği açısından özgün katkılar sunmaktadır.

Anahtar Kelimeler: Enerji Verimliliği, Yenilenebilir Enerji, Karbon Emisyonları, Çevresel Sürdürülebilirlik, Toda-Yamamoto Nedensellik Testi

Abstract

This study aims to examine the relationships between energy efficiency, renewable energy consumption, and carbon emissions in Turkey's energy sector while proposing policy recommendations for environmental sustainability. The study utilizes data from 2000 to 2022 and applies econometric methods such as the Dickey-Fuller Generalized Least Squares (DF-GLS) unit root test and the Toda-Yamamoto causality test. The results reveal a unidirectional causality between energy efficiency and carbon emissions at the 5% significance level, indicating that energy efficiency is an effective tool for reducing carbon emissions. However, no significant causal relationship was found between renewable energy consumption and carbon emissions. This finding underscores the need to enhance renewable energy infrastructure and strengthen related policies. The study highlights that the effectiveness of energy efficiency and renewable energy policies is influenced by country-specific conditions. In the context of Turkey's energy sector, it recommends promoting energy-saving technologies, increasing investments in renewable energy, and implementing environmental policies such as carbon taxes. Additionally, the study emphasizes the importance of international cooperation and the development of regional renewable energy projects. These recommendations can contribute to achieving Turkey's sustainable development goals. The findings provide unique insights into the impact of energy efficiency on carbon emissions and the effectiveness of renewable energy policies, making a valuable contribution to the literature.

Keywords: Energy Efficiency, Renewable Energy, Carbon Emissions, Environmental Sustainability, Toda-Yamamoto Causality Test

1. INTRODUCTION

Global climate change, rising energy demand, and environmental degradation are among the most significant challenges facing humanity, making the construction of a sustainable future increasingly difficult. Since the mid-20th century, a period marked by accelerated industrialization, economic growth driven by fossil fuel consumption has led to dramatic increases in carbon dioxide (CO2) emissions. Currently, the energy sector accounts for approximately two-thirds of global greenhouse gas emissions, making it a primary driver of climate change (Dincer, 2000, p. 157). This situation has underscored the necessity of developing more environmentally friendly and sustainable energy production methods.

Energy efficiency is regarded as one of the most effective strategies for achieving environmental sustainability. It focuses on obtaining the same energy output with reduced energy input, thereby mitigating the environmental impacts of energy production and consumption processes (Herring, 2006, p. 12). Beyond its environmental benefits, energy efficiency also provides significant economic advantages by lowering energy costs. For instance, the widespread adoption of energy-saving technologies reduces energy expenses for individuals and businesses alike and positively affects trade balances by decreasing energy import dependency at the national level (Elliott, 2000, p. 263).

Alongside energy efficiency, renewable energy constitutes a cornerstone in the fight against climate change. Renewable energy sources, such as hydropower, solar, wind, and biomass, offer alternatives to the environmental harms of fossil fuels, with the potential to significantly reduce carbon emissions (Masoudi et al., 2020, p. 97). While the history of renewable energy dates back to the early 20th century, the oil crises of the 1970s prompted countries to take these resources more seriously. During this period, nations aiming to reduce energy dependence increased investments in renewable energy and developed policies to encourage its use (Dincer & Rosen, 1999, p. 430). Today, renewable energy has been prioritized under the framework of the United Nations Sustainable Development Goals (SDGs) and has become a focal point of global collaboration. At the international level, numerous cooperative mechanisms and policy frameworks have been developed to promote energy efficiency and the use of renewable energy. The United Nations Framework Convention on Climate Change (UNFCCC) and its Conferences of the Parties (COP) have encouraged countries to adopt binding targets for reducing carbon emissions. The Paris Agreement, signed in 2015, emphasized the importance of transitioning to renewable energy in its goal of limiting global warming to 1.5°C above pre-industrial levels. Moreover, the International Renewable Energy Agency (IRENA) offers innovative solutions and policy recommendations to support member states in their energy transition processes (Masoudi et al., 2020, pp. 97–98). Similarly, renewable energy and energy efficiency remain central topics in G7 and G20 summits, aligning with policies for economic development and environmental sustainability.

Although the literature contains numerous studies examining the environmental impacts of energy efficiency and renewable energy, most of these works focus on general trends without delving into the specific relationships between different countries' energy profiles and environmental impacts (Hanley et al., 2008, p. 700). For instance, the effects of energy efficiency policies in low-emission countries differ significantly when compared to high-emission counterparts (Zakari et al., 2022, p. 1166). Additionally, the extent to which renewable energy impacts emissions remains underexplored in terms of how factors like economic structure, energy consumption patterns, and technological innovation influence outcomes (Rahman & Alam, 2022, p. 205).

This study aims to address this critical gap in the literature by thoroughly examining the relationships between energy efficiency, renewable energy usage, and CO2 emissions. It analyzes the environmental impacts of renewable energy and energy efficiency policies using diverse country examples, offering recommendations to enhance policy effectiveness. In doing so, the study seeks to contribute to the development of more effective and inclusive strategies for policymakers.

The remainder of this paper is organized as follows: The theoretical framework explores the relationships between renewable energy, energy efficiency, and CO2 emissions in detail. The methodology section introduces the dataset and analytical methods employed. The findings and discussion section presents the results of the analyses and links them to the existing literature. Finally, policy recommendations and suggestions for future research are outlined in the conclusion section.

2. THEORETICAL FRAMEWORK

Energy efficiency and renewable energy resources play a critical role in ensuring environmental sustainability and combating climate change. Fossil fuel-based energy consumption is recognized as one of the primary drivers of global warming and environmental degradation, underscoring the urgent need for cleaner and more innovative energy solutions. In this context, theoretical studies on energy efficiency and renewable energy provide a solid foundation for understanding both environmental and economic impacts and for designing effective policies in these areas.

Theories of energy efficiency focus on achieving the same or greater output with reduced energy input. These theories emphasize not only environmental benefits but also economic gains. Herring (2006) highlights the potential of energy efficiency to reduce carbon emissions, while discussing the "rebound effect," where cost savings from energy efficiency may inadvertently lead to an overall increase in energy consumption (Hanley et al., 2008, p. 700). This theory underscores the need for comprehensive energy policies to ensure the realization of the potential benefits of energy savings.

Energy efficiency theories are closely linked to economic sustainability. Elliott (2000) underscores that energy efficiency technologies provide cost savings for individuals and businesses while positively contributing to trade balances. Energy efficiency not only mitigates environmental impacts but also enhances national security by reducing energy dependency. This is particularly crucial for developing countries, as reduced energy costs can create resources to support economic growth.

Renewable energy theories address the role of alternative resources to fossil fuels in ensuring environmental sustainability and energy security. Dincer (2000) emphasizes the potential of renewable energy sources to mitigate environmental damage and reduce carbon emissions. These sources are also highlighted as critical tools for enhancing energy security. Renewable energy contributes to reducing environmental impacts while creating economic opportunities. For instance, solar and wind energy projects generate employment opportunities and deliver economic benefits to local communities.

These theories are further supported by global collaborations and policy frameworks. The Paris Agreement, signed in 2015, highlighted the priority of investing in renewable energy and adapting to climate change (Zakari et al., 2022, p. 1166). Masoudi et al. (2020) assert that renewable energy usage supports economic growth and reduces carbon emissions. Investments in renewable energy can help bridge energy inequalities between developed and developing countries.

Theories of energy efficiency and renewable energy focus not only on environmental benefits but also on their economic and social impacts. Rahman and Alam (2022) examine the role of industrialization, financial development, and renewable energy usage in enhancing environmental sustainability. Their study highlights that investments in the energy sector yield social benefits, such as job creation in local economies. The adoption of renewable energy technologies at the local level can increase energy access rates and diversify energy supply, particularly supporting economic development in developing countries.

In conclusion, the theories of energy efficiency and renewable energy form a comprehensive framework that integrates environmental sustainability, economic gains, and social benefits. This theoretical foundation not only supports the development of eco-friendly policies but also strengthens global collaborations. By guiding academic and practical studies in this field, these theories provide a robust basis for future research.

3. LITERATURE REVIEW

Dincer and Rosen (1999) analyzed the environmental impacts of energy efficiency and renewable energy technologies by examining the connection between energy, the environment, and sustainable development. They emphasized the importance of reducing fossil fuel consumption and enhancing energy efficiency within the framework of sustainable development. In a related study, Dincer (2000) explored the effects of renewable energy sources on environmental sustainability and their relationship with sustainable development, highlighting that broader utilization of energy types such as solar, wind, biomass, and geothermal could mitigate environmental damage. Elliott (2000) investigated renewable energy policies in countries like Denmark, the United Kingdom, and Germany, emphasizing the significance of local ownership models.

Kaygusuz and Kaygusuz (2002) addressed Turkey's renewable energy potential, energy efficiency, and their roles in sustainable development, drawing attention to the importance of resources such as hydropower, solar, and geothermal energy. Herring (2006) argued that energy efficiency might increase energy consumption due to the "rebound effect" and suggested carbon taxes and a transition to renewable energy as more effective policies. Similarly, Ayres et al. (2007) posited that energy efficiency could support economic growth while reducing greenhouse gas emissions and proposed policies to improve energy transformation efficiency.

Hanley et al. (2008) examined multi-regional environmental input-output analyses for Scotland's economy and assessed the impacts of carbon trading and reduced energy intensity on sustainable development. Panwar et al. (2011) highlighted the role of renewable energy resources in economic development and energy security, suggesting that diversifying these resources could enhance both economic and environmental benefits. Bhattacharya et al. (2016) revealed a long-term positive relationship between renewable energy consumption and economic growth. Similarly, Sinha and Shahbaz (2018) emphasized the positive impact of renewable energy consumption on environmental sustainability, noting its potential to support sustainable economic growth.

Sarkodie and Adams (2018) analyzed the effects of discrete and combined energy consumption on environmental pollution in South Africa. Their study highlighted the impacts of transitioning from fossil fuels to renewable energy on economic growth and environmental sustainability, showing that institutional policy quality plays a crucial role in reducing environmental pollution. Furthermore, Wang et al. (2019) assessed industrial energy consumption and emission reduction policies in China, emphasizing the positive effects of renewable energy investments on carbon reduction. Zakari et al. (2022) examined the link between sustainable development goals and energy efficiency in 20 Asia-Pacific countries, demonstrating that green innovation enhances energy efficiency and contributes to economic sustainability. Rahman and Alam (2022) investigated the effects of industrialization, renewable energy use, and financial development on environmental pollution in Australia, underlining the importance of renewable energy policies. Zhang et al. (2022) evaluated the relationship between renewable energy, green finance, and financial inclusion in China, noting that green finance fosters innovation. Lastly, studies supported by the International Renewable Energy Agency (IRENA) highlighted the role of renewable energy policies in reducing inequalities between countries. These studies comprehensively reveal the environmental impacts of energy efficiency and renewable energy sources while guiding future policies and strategies.

4. DATA SET AND METHODOLOGY

In this study, the econometric model was constructed using data from the period between 2000 and 2022. The primary objective of the study is to analyze the relationship between carbon emissions in Turkey and indicators such as energy efficiency and renewable energy consumption, providing recommendations for sustainability policies in the energy sector. The dependent variable in the model is carbon emissions from the energy sector (ECO2). This variable was chosen to represent the environmental impacts of the energy sector and the level of greenhouse gas emissions.

The independent variables include energy efficiency (EE) and the share of renewable energy consumption in total final energy consumption (REC). The EE variable was included in the model to analyze the efficient use of energy and its impact on carbon emissions. The REC variable was used to evaluate the potential of renewable energy usage in reducing carbon emissions.

The data used in the model were organized on an annual basis, aiming to provide a holistic assessment of the environmental, economic, and social impacts of the energy sector. Descriptive information regarding the data used in the study is presented in Table 1.

Table 1. Descriptive Information on Variables

Variable	Notation	Definition	Usage	Source
CO2	lnCO2	Carbon dioxide (CO2) emissions from the energy sector (Mt CO2e)	Logarithmic	https://databank.worldbank.org/source/world-development-indicators
EE	lnEV	Energy efficiency (kilograms of oil equivalent per Euro (KGOE))	Logarithmic	https://ec.europa.eu/eurostat/web/main/data/database
REC	YEP	Renewable energy consumption (as % of total final energy consumption)	Non-logarithmic	https://databank.worldbank.org/source/world-development-indicators

All variables, except for “REC,” have been transformed into their natural logarithmic forms to ensure that observations with different unit values are expressed on a comparable scale. The notation “ln” indicates that the series has been logarithmically transformed. The model used in the analysis is presented in Equation 1:

$$lnCO2_t = \beta_0 + \beta_1 lnEV_t + \beta_2 YEP_t + \varepsilon_t \qquad (1)$$

The model analyzed in this study is presented in Equation (1). In the econometric model specified in Equation (1), the notations β0 and εt represent the constant term and the error term, respectively. The parameters β1 to β2 denote the coefficients of the explanatory variables included in the function.

In the first stage of the study, the stationarity levels of the series were determined using the Dickey-Fuller Generalized Least Squares (DF-GLS) unit root test, a traditional method for identifying unit roots. Subsequently, based on the stationarity levels of the series, the Toda-Yamamoto (1995) causality test was employed, following the appropriate methodology outlined in the literature.

4.1. Unit Root Test

The Dickey-Fuller Generalized Least Squares (DF-GLS) test, developed by Elliott, Rothenberg, and Stock (1996), is a unit root test that provides stronger and more effective results compared to the Augmented Dickey-Fuller (ADF) test due to its asymptotic distribution properties.

To apply the DF-GLS test, time series data must first be detrended. The detrending process is performed based on the regression equation provided below:

$$\Delta x_t^d = \beta_1 x_{t-1}^d + \sum_{i=1}^{k} \lambda_i \Delta x_{t-i}^d + \varepsilon_t$$
(2)

In the equation (2) , x_t^d, represents the series detrended using the DF-GLS method. In this test, the coefficient β1 serves as the basis for evaluating the stationarity of the series. If the null hypothesis (β_1= 0) is rejected in the estimated equation, it is concluded that the series x_t is stationary (Ceylan & Durkaya, 2010, p. 27).

4.2. Toda-Yamamoto (1995) Causality Test

The Toda-Yamamoto (1995) causality test is a widely used method for examining causal relationships between time series variables, regardless of their integration orders. Unlike traditional Granger causality tests, which require all variables to be stationary at the same level, the Toda-Yamamoto approach can handle variables with different levels of integration (I(0), I(1), or a mix). This makes it particularly suitable for datasets that include non-stationary series.

In the Toda-Yamamoto (1995) causality analysis, the Wald test is applied. The distribution of the Wald test corresponds to the χ2 distribution, calculated by summing the number of lags in the VAR model with the integration order of the series. The Toda-Yamamoto causality test constructs a standard VAR model at the level values of the variables, effectively eliminating the issues that arise when determining the cointegration orders of the series (Duasa, 2007, p. 87; Zapata & Rambaldi, 1997, p. 289). Accordingly, the VAR models are formulated as follows:

$$lnX_t = \sum_{i=1}^{k+d_{max}} \alpha_{1i} lnX_{ti} + \sum_{i=1}^{k+d_{max}} \beta_{1i} lnY_{ti} + \varepsilon_{1t}$$
(3)

$$lnY_t = \sum_{i=1}^{k+d_{max}} \alpha_{2i} lnY_{ti} + \sum_{i=1}^{k+d_{max}} \beta_{2i} lnX_{ti} + \varepsilon_{2t}$$
(4)

The relationships in the Toda-Yamamoto causality test can be represented in equations (3) and (4). In these equations, d_{max} represents the maximum order of integration of the variables, while k denotes the optimal lag length determined for the VAR model. ε_t is included as the error correction term under the white noise assumption.

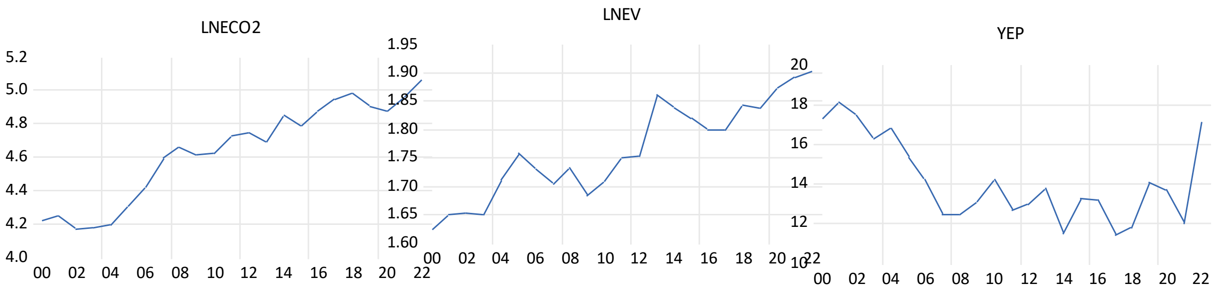
In equation (3), under the condition i ≤ k, the null hypothesis $\beta_{1i} = 0$ is tested. If the alternative hypothesis is accepted, no causality relationship is found from $Y_t$to X_t. For equation (4), under the condition i ≤ k, the null hypothesis ($\beta_{2i} = 0$) is tested. If the alternative hypothesis is accepted, a causality relationship from X_t to Y_t is established.

5. FINDINGS

Since the averages of most time series tend to increase over time, classic regression models may encounter the problem of spurious regression. To address this issue, unit root testing is essential for assessing stationarity. Accordingly, unit root tests have long been utilized as a preliminary step in econometric analyses in the literature. In this study, the DF-GLS unit root test was applied to examine the stationarity characteristics of the series.

When examining the graphs of the variables used in the study, it was observed that the series exhibited significant trends. This excessive trending could lead to misleading results in stationarity tests conducted using traditional methods. Therefore, to remove the trends and accurately assess stationarity, the DF-GLS unit root test was included in the analysis. The graphs of the series are presented in Figure 1:

Figure 1: Time Paths of the Variables



The DF-GLS test stands out for its ability to enhance the accuracy of stationarity analysis by eliminating deterministic trends in the series. This method enables a more reliable assessment of the structural characteristics of the series, thereby increasing the credibility of the analysis results. The findings of the DF-GLS and PP unit root tests are presented in Table 2:

Table 2: Results of DF-GLS and PP Unit Root Tests

DF-GLS	Level I(0)	
Variable	*Constant*	*Constant + Trend*
lnCO2	-0.117(0)	-2.201(0)
lnEV	-0.642(0)	-3.091(0)*
YEP	-1.840(0)	-2.007(0)
	First Difference I(1)	
DlnCO2	-4.227(0)***	-4.208(0)***
DlnEV	-5.221(0)***	-5.261(0)***
DYEP	-1.376(2)	-5.098(1)***

Note: The symbols *, **, and *** indicate significance levels at 10%, 5%, and 1%, respectively. The notation "D" signifies that the first difference of the series has been taken. In the DF-GLS test, the values in parentheses represent the optimal lag lengths determined using the Schwarz

Information Criterion (SIC). The critical values for the DF-GLS test were sourced from the critical value tables developed by Elliott et al. (1996). This approach ensures a robust determination of stationarity levels, enhancing the reliability of the analysis.

According to the results of the DF-GLS unit root test, when stationarity is evaluated at the level I(0), the carbon emissions variable is found to be non-stationary as the test statistics in the constant model (-0.117) and the constant + trend model (-2.201) are smaller than the critical values. The energy efficiency variable exhibits stationarity at the 10% significance level in the constant + trend model (-3.091) as its test statistic is greater than the critical value; however, it is non-stationary in the constant model. Renewable energy consumption, on the other hand, is non-stationary in both models (-1.840 and -2.007), as the test statistics are smaller than the critical values. These results indicate that only the energy efficiency variable shows limited stationarity at the level, while the other variables are non-stationary at this level.

When the first differences I(1) of the variables are analyzed, the first difference of carbon emissions is stationary at the 1% significance level in both the constant (-4.227) and constant + trend (-4.208) models, as the test statistics are greater than the critical values. Similarly, the first difference of the energy efficiency variable is stationary at the 1% significance level in both the constant (-5.221) and constant + trend (-5.261) models. The first difference of renewable energy consumption is stationary at the 1% significance level in the constant + trend model (-5.098), as its test statistic is greater than the critical value; however, it is non-stationary in the constant model (-1.376), as the test statistic is smaller than the critical value. These findings reveal that the first differences of carbon emissions, energy efficiency, and renewable energy consumption generally exhibit stationarity, though stationarity is not achieved for renewable energy consumption in the constant model.

In summary, while only the energy efficiency variable exhibits limited stationarity at the level, the other variables are non-stationary. At the first difference, the variables for carbon emissions, energy efficiency, and renewable energy consumption largely demonstrate stationarity. These results suggest that in the modeling process, the energy efficiency variable can be considered stationary at the level, whereas the other variables should be treated as stationary at the first difference. This indicates that the ARDL model, which accommodates a mix of I(0) and I(1) variables, provides an appropriate framework for this analysis.

Based on the results from the unit root tests, the maximum order of integration for the variables is determined to be 1. To address this, the maximum stationarity degree was added to the optimal lag length in all models, ensuring that the testing process did not result in data loss or reduced observations caused by differencing. This approach is believed to yield stronger results. For the application of the Toda-Yamamoto test, a VAR model must first be established to determine the appropriate lag length. The table below presents the results for selecting the optimal lag length.

Table 3: Determination of Optimal Lag Length with VAR Model

Lag	LR	FPE	AIC	SC	HQ
0	NA	0.000237	0.164963	0.314085	0.190201
1	53.04956*	1.81e-05*	-2.424306	-1.827818*	-2.323356
2	3.512011	3.81e-05	-1.769605	-0.725751	-1.592943
3	16.14378	2.09e-05	-2.615990	-1.124771	-2.363616
4	7.215632	2.84e-05	-2.871227*	-0.932642	-2.543141*

According to the results presented in Table 3, the lag length of the model was determined as 1 based on the Schwarz Information Criterion (SC), Final Prediction Error (FPE), and the Sequential Modified LR Test Statistic (LR). Using these results, the optimal lag length (ppp) was selected as 1, as it incorporates multiple information criteria and is a commonly applied method in practice.

Following the determination of the appropriate lag length, the LM test was conducted to identify whether there were autocorrelation issues at this lag length. The results of the autocorrelation test for the model with a lag length of 1 are presented in Table 4:

Table 4: Autocorrelation LM Test Results

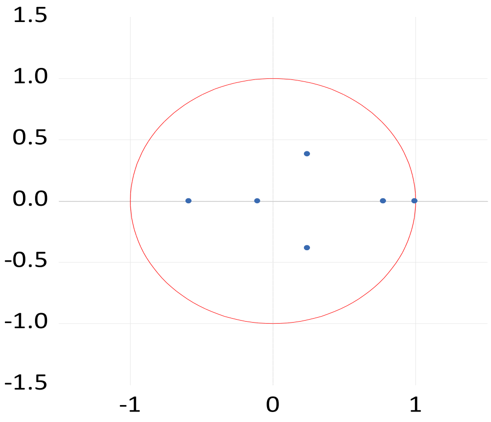
Lagrange Multiplier (LM) Autocorrelation Test		
Lag Length	LM Test Statistic	Probability Value
1	14.810	0.101
2	12.831	0.176
3	11.088	0.277

Ho: There is no autocorrelation.

H1: There is autocorrelation.

According to the results presented in Table 4, the hypothesis stating that there is no autocorrelation for the optimal lag length (p=1) and other lag lengths is accepted. In Figure 2, it is observed that all the inverse roots of the AR characteristic polynomial for the VAR model with a lag length of 1 lie within the unit circle, indicating that the model is stationary.

Figure 2: Inverse Roots of AR Characteristic Polynomials



Due to the different stationarity levels of the series, i.e., I(0) and I(1), the Toda-Yamamoto causality test was deemed appropriate for investigating causality. Accordingly, the maximum integration order obtained from the unit root tests (dmax=1), was added to the optimal lag length determined from the VAR model (p=1), resulting in the construction of a VAR(1+1) model. No autocorrelation issues were detected in the model. Based on the results of the established VAR(1+1) model, the inverse roots of the AR polynomial lie within the unit circle, satisfying the stability conditions.

Table 5: Toda-Yamamoto Causality Test Results

Direction of Causality			Lag Length p=1 dmax=1 (p+dmax=2)	Wald Statistic	p-Value
Lnev	→	Lneco2	2	4.354**	0.036
Yep	→	Lneco2	2	0.446	0.503
Lneco2	→	Lnev	2	0.005	0.940
Yep	→	lnev	2	0.008	0.925
Lneco2	→	yep	2	0.011	0.914
lnev	→	yep	2	0.358	0.549

According to the Granger causality results, there is a unidirectional causality from energy efficiency (lnEV) to carbon emissions (lnCO2) at the 5% significance level. No other Granger causality relationships were found to be statistically significant among the variables.

Based on Table 5, a unidirectional causal relationship exists between energy efficiency (lnEV) and carbon emissions (lnCO2). The causality from energy efficiency to carbon emissions is statistically significant at the 5% level (Wald statistic: 4.354, p-value: 0.036). This result indicates that changes in energy efficiency have a causal effect on carbon emissions.

On the other hand, no significant causal relationship was identified between the share of renewable energy consumption (YEP) and carbon emissions (Wald statistic: 0.446, p-value: 0.503). Similarly, no causality was found from carbon emissions to energy efficiency (Wald statistic: 0.005, p-value: 0.940) or to renewable energy consumption (Wald statistic: 0.011, p-value: 0.914). Furthermore, there is no significant causality from renewable energy consumption to energy efficiency (Wald statistic: 0.008, p-value: 0.925) or from energy efficiency to renewable energy consumption (Wald statistic: 0.358, p-value: 0.549).

These findings suggest that energy efficiency can influence carbon emissions, but no significant causal relationships were detected among other variable pairs. From a policy perspective, this highlights that improving energy efficiency could be an effective tool for reducing carbon emissions. However, the lack of causal relationships involving renewable energy consumption indicates the need for further detailed research in this area.

6. DISCUSSION

The findings of this study reveal a unidirectional causal relationship between energy efficiency (lnEV) and carbon emissions (lnCO2) at the 5% significance level. It was concluded that changes in energy efficiency could influence carbon emissions. This finding aligns with the literature emphasizing the impact of energy efficiency policies on environmental sustainability. For instance, Herring (2006) suggested that energy efficiency could reduce carbon emissions but noted that this effect might be limited due to the "rebound effect." In this context, the results obtained provide a clearer understanding of the environmental impacts of energy efficiency, contributing to the existing literature.

No causal relationship was found between renewable energy consumption (YEP) and carbon emissions or energy efficiency. This finding appears to contradict studies such as Panwar et al. (2011) and Bhattacharya et al. (2016), which emphasize the positive impacts of renewable energy use on environmental sustainability. However, this discrepancy can be explained by Turkey's specific energy consumption profiles, the development of renewable energy infrastructure, and limited technological innovations. Particularly, the findings of Dincer (2000) and Kaygusuz & Kaygusuz (2002), which highlight that the effective use of renewable energy sources is constrained by infrastructure and policy shortcomings, support the results of this study.

The literature indicates that the environmental impacts of energy efficiency and renewable energy policies may vary depending on country profiles and economic structures (Rahman & Alam, 2022; Zakari et al., 2022). The absence of a significant causal relationship between renewable energy consumption and carbon emissions in this study suggests a need for more comprehensive implementation and infrastructure development in this policy area.

In conclusion, while the relationship between energy efficiency and carbon emissions aligns with general trends in the literature, different results were obtained regarding the impact of renewable energy consumption. This highlights the role of country-specific policy and implementation differences in determining the effectiveness of energy policies.

7. CONCLUSION

This study examined the relationships between energy efficiency, renewable energy consumption, and carbon emissions within the context of Turkey's energy sector, evaluating their significance for environmental sustainability. The theoretical framework discussed the impacts of energy efficiency and renewable energy policies on environmental sustainability, highlighting their economic and environmental implications. Additionally, the current structure of the energy sector and the challenges it faces in aligning with sustainable development goals were analyzed.

In the introduction, it was emphasized that global energy crises, rising energy demand, and climate change have heightened the importance of sustainable energy policies. Particularly, it was noted that economic growth driven by fossil fuels has exacerbated carbon emissions, leading to environmental degradation. In this context, energy efficiency and renewable energy usage were identified as key tools for addressing these issues.

The study's findings revealed that energy efficiency has a statistically significant impact on carbon emissions, whereas renewable energy consumption does not exhibit a meaningful causal relationship with carbon emissions or energy efficiency. The unidirectional causality observed between energy efficiency and carbon emissions indicates that policies aimed at enhancing energy efficiency could serve as an effective tool for reducing carbon emissions. This finding underscores the strategic role of energy efficiency policies not only for environmental sustainability but also for economic benefits and energy security.

On the other hand, the lack of a detectable impact of renewable energy consumption on carbon emissions suggests the need for further development of renewable energy infrastructure and policies in Turkey. While the literature frequently highlights the role of renewable energy sources in promoting environmental sustainability, the findings of this study indicate that more comprehensive applications and technological innovations are required in the Turkish context.

In conclusion, this study provided valuable contributions to the literature by investigating the effects of energy efficiency and renewable energy consumption on environmental sustainability. The findings highlight the critical role of energy efficiency in reducing carbon emissions, while emphasizing the need for more effective implementation of renewable energy policies. These results suggest that energy policies should be designed in accordance with country-specific conditions and point to the necessity of adopting a more holistic approach in this process.

8. POLICY RECOMMENDATIONS

Based on the findings of this study, a series of policy recommendations have been developed to enhance the effectiveness of energy efficiency and renewable energy policies in promoting environmental sustainability. First and foremost, strategies to improve energy efficiency should be prioritized, considering its proven effectiveness in reducing carbon emissions. The widespread adoption of energy-saving technologies and the implementation of regulations aimed at increasing energy efficiency in sectors such as industry, housing, and transportation are of critical importance. Additionally, educational and awareness campaigns should be organized to promote energy efficiency.

Given the limited impact of renewable energy consumption on carbon emissions, strengthening renewable energy infrastructure should be another key priority. Investments in renewable energy sources, such as solar, wind, biomass, and geothermal, should be increased, and the integration of energy storage technologies should be encouraged. Research and development (R&D) initiatives aimed at fostering domestic renewable energy technologies should be financially supported, and innovative projects in this area should be incentivized.

Financial incentives and tax policies should be designed to support energy-related policies. Providing tax benefits and low-interest loans for projects that reduce carbon emissions can attract greater interest from investors. Simultaneously, the implementation of carbon taxes could disincentivize the use of fossil fuels, accelerating the transition to sustainable energy solutions. To enhance the effectiveness of energy policies, a comprehensive strategy that includes sector-specific targets and aligns with international standards should be developed. Long-term plans to increase Turkey’s renewable energy capacity should be established, and their implementation should be regularly monitored.

Furthermore, strengthening international cooperation is another essential policy area. Turkey should expand its collaboration with international organizations in the fields of renewable energy and energy efficiency while leveraging global funds in this domain. Joint projects can be developed within the framework of the European Union Green Deal, and relations with organizations such as the International Renewable Energy Agency (IRENA) can be further deepened.

Finally, the regional applicability of energy policies should be enhanced. Considering regional characteristics and energy needs, pilot projects could be implemented in areas with high renewable energy potential. Such regional initiatives would contribute to both local economies and national energy policies. These recommendations aim to support Turkey in achieving its environmental sustainability goals while fostering long-term transformation in the energy sector.

Statement Regarding the Data Used in This Study

All data used in this study can be made available to interested researchers or readers upon request. Data sharing will be conducted solely for academic purposes and in accordance with ethical guidelines. For inquiries, please contact [ahmet.kasap@gop.edu.tr].

Author Contribution Statement

This study was conducted entirely by a single author, with a 100% contribution rate. All stages of the research, including the development of the research idea, literature review, data analysis, interpretation of results, and writing process, were completed solely by the author.

Conflict of Interest Statement

The author declares that there is no conflict of interest with any individual, institution, or organization in the preparation, evaluation, or publication of this study.

Ethical Statement and Conflict of Interest

This study has been conducted, prepared, and published without any ethical violations or issues. Furthermore, the author declares that there is no conflict of interest with any individual, institution, or organization related to this study.

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